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A FREQUENCY-MODULATED INSTRUMENTATION SYSTEM FOR HIGH-EXPLOSIVE GROUND MOTION, AIRBLAST, AND STRUCTURE RESPONSE TESTS

February 1977

Final Report

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An analysis of currently used data transfer systems for instrumentation provides several options for improvement. These options are examined in light of modern integrated circuit technology and one option explored. This results in a detailed specification and design for a system which was built and tested. The system provides eight FM multiplex channels of ten kilohertz data.

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SECTION I

DATA TRANSFER SYSTEM OPTIONS

The measurement of various physical phenomena associated with high exposive testing as performed by the Civil Engineering Division of the Air Force Weapons Laboratory is accomplished by an instrumentation system. This system's function is to convert the phenomena to be measured (measurand) into a form with which human beings may intelligently interact.

With few exceptions, the primary carrier of information is an electrical parameter--either voltage or current. As most human beings do not interact well with these electrical signals, devices have been developed to convert these parameters to meaningful visual or aural displays. This forms the basis for examining the instrumentation system. It essentially: (1) converts the test phenomena to be measured to electrical form, (2) carries that electrical signal to a convenient location, and (3) converts the signal to a meaningful visual form.

This report will be concerned with that portion of the instrumentation system after the measurand has been converted to electrical form by a device called a transducer. This portion of the system is described here as a data transfer system. A typical instrumentation system is shown in figure 1.

It should be noted that the output of the data transfer system is at the mercy of the weakest link in that system.

The type and length of signal line are determined by many factors of which two may be cost and safety. Generally, good quality cable is expensive and may improve the signal quality. Safety of personnel and equipment may dictate the required length or distance from the test bed.

The signal conditioner typically amplifies the signal such that any noise introduced later is relatively small compared to the new signal level. The signal conditioner may also support the transducer with power and possibly calibration.

The voltage controlled oscillator (VCO) is a means of preparing the signal for the tape recorder. It may also act as a frequency multiplexer when several data signals are to be recorded on one recorder track.

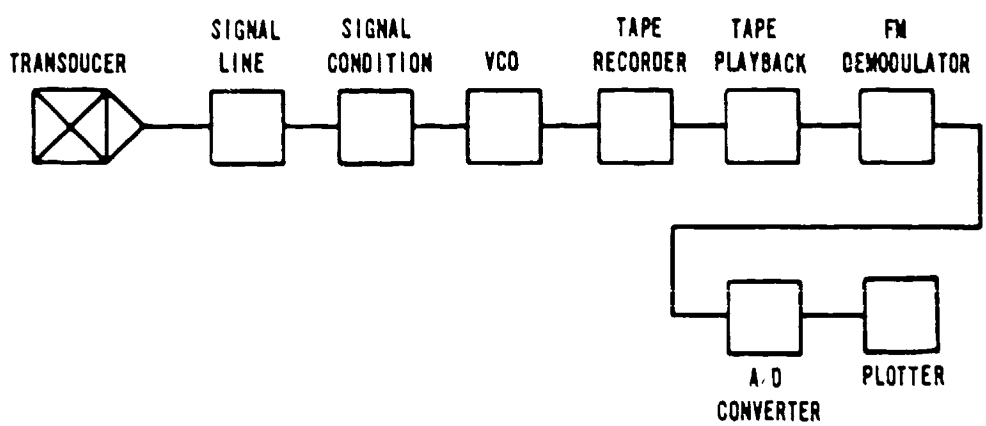


Figure 1. Typical Instrumentation System

The tape recorder is a means of permanent signal storage, and the resulting tapes are also a method of transportation for the recorded data. The tape playback unit recovers the data in electrical form at which time it is demodulated to original electrical form, converted to a digital signal and, with the help of a computer, displayed on paper plots by the readout device.

A careful study of figure 1 reveals certain optional methods of placement of the various items. If the appropriate hardware is available, it is apparent that the position of the signal line is negotiable among various points in the data transfer system. Indeed it is possible that the signal line could be eliminated completely. In other words, the signal line may be placed between the signal conditioner and the voltage controlled oscillator or between the voltage controlled oscillator and the tape recorder. And, lastly, the tape recorder, along with the signal conditioner and the VCO, may be moved next to the transducer eliminating the need for the signal line.

The current state-of-the-art in tape playback, FM demodulation, A/D conversion, and readout devices is such that these portions contribute very little to the noise or distortion of the signal and are thus among the stronger links in the chain.

Since low-cost signal line is currently the weakest link in the system in that it adds the most distortion and noise, this report will cover one of the options mentioned earlier and discuss the needed hardware.

SECTION II

A COST-EFFECTIVE APPROACH

In earlier work (ref. 1), hardware was described which moved the signal conditioning circuits to the transducer; thus placing the signal line between it and the VCO. This was shown to considerably reduce the noise and distortion. The economics in terms of cable splicing manhours and amount of cable needed was also improved. However, the economics may be improved even further when it is realized that the VCO, along with the VCO mixer, performs the task of multiplexing several signals on a wide band channel. If the signal line may be made wide band and the VCO placed near the transducer, a further savings in cable is possible. However, in this case, the cable must have a high bandwidth capability. This system is shown in figure 2.

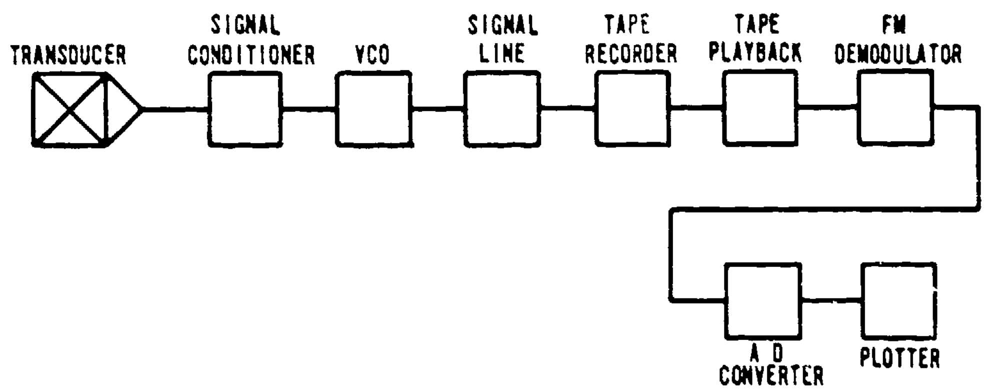


Figure 2. Proposed Improved Instrumentation System

1. Ray, D. J., "Self Conditioning Transducers," Instrumentation Tecnnology, September 1976, pp. 69-73.

SECTION III

FREQUENCY MODULATION AND FREQUENCY DIVISION MULTIPLEXING

The superiority of FM over amplitude modulation in the presence of noise and interference is clear from examining the sideband structure. An FM signal has a great number of sidebands in which the frequency, magnitude and phase of each has a precise relationship to the carrier. That is to say, FM has a coherent sideband structure and the information is, therefore, redundantly transmitted many times over. In addition, if the FM carrier frequency for each of several channels is sufficiently different, then the outputs of several such systems may be added and sent over one cable in the form of frequency division multiplexing. Now an amount of cable may also be saved without loss or degradation of data.

In practical systems, certain nonlinearities appear in the hardware that may render the above-described system less than useful. The greatest of these is the square wave producing voltage controlled oscillator (VCO). The commonly used VCO produces a train of pulses, each with the same amplitude but with a period proportional to the input voltage. This in itself is not a problem except when frequency division multiplexing is also required. The square wave VCO output not only contains the normal FM spectrum around the square wave fundamental frequency but also contains the data spectrum around all the odd harmonics of the fundamental. It is the third harmonic frequency (amplitude of about 42% of the original signal) which complicates the multiplexing scheme as the harmonics of the lower VCO's may fall in the signal bands of the higher VCO's. The common method of dealing with this problem is to place multipole filters on the outputs of the VCO's. This further complicates the system, may be expensive, and may also distort the recovered data signals. It is the implementation of the FM concept by use of square wave generating voltage controlled oscillators that creates the expense of presently used FM multiplexing systems. It is now appropriate to introduce the sine wave function generator.

Advances in integrated circuits have brought out the Monolithic Voltage Controlled Function Generator, capable of producing high quality sine wave outputs with a total harmonic distortion of one-half a percent or less. The technique used in most sine wave function generators is to produce a normal VCO triangular wave and then send it through a sine shaping circuit as in figure 3.

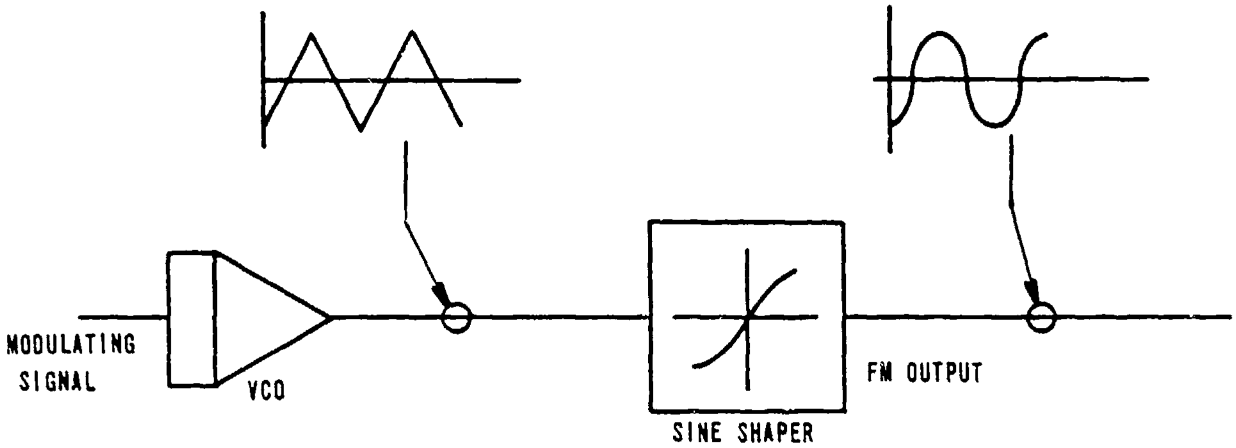


Figure 3. Sine Wave Function Generator

SECTION IV

SPECIFICATIONS FOR THE PROPOSED SYSTEM

The number of multiplexed data channels is limited by the bandwidth of the long line link connecting the forward multiplex system to the protected van position. The practical limit in this case for one mile of RG58 coaxial cable is one megahertz. This value is also specified as the upper limit of the typical Sine Wave Function Generator.

If the deviation from center frequency of an FM signal is a very small percent of the center frequency, the signal-to-noise ratio of the recovered signal will suffer. In this paper we will accept 3.5 to 40 percent. In a constant bandwidth system, the highest frequency VCO will have the smallest percentage of deviation. At 848 kHz (which is the greatest practical frequency for the proposed system as will be shown later) the 3.5 percent figures require a deviation of about 30 kHz.

It is well known that the true bandwidth of an FM signal is not just the total frequency swing but is instead a much larger value. Carlson (ref. 2) gives the effective bandwidth (BW) as

$$BW = 2(D + 2)\, f_{s\ max}$$

where D is the deviation ratio defined as $f_{d\ max}/f_{s\ max}$. $f_{s\ max}$ is the highest frequency contained in the input modulating signal. The expression for the bandwidth just given is understood to apply only if D is greater than two. This system will use D equal to three. The importance of deciding on a value for $f_{s\ max}$ is now apparent. If $f_{s\ max}$ is too large, excessive bandwidth will be used. If $f_{s\ max}$ chosen for the system is smaller than the actual $f_{s\ max}$ of the signal, the recovered output will be distorted. For this paper, the results for an $f_{s\ max}$ of 10 kHz are presented. The bandwidth defined in equation (1), along with the decision to provide 12 kHz of guard band space, now tells us the maximum number of channels of data that may be included in a 1 MHz composite

2. Carlson, Communication Systems: An Introduction to Signals and Noise in Electrical Communications, McGraw Hill, New York, N.Y., 1968.

signal bandwidth. Table 1 gives the important parameters for $f_{s\ max}$ of 10 kHz and for $f_{d\ max}$ of 30 kHz. A clear space in the spectrum must also be allocated for the reference oscillator.

FM Bandwidth	D	Number of Data Channels in 1 MHz
100 kHz	3.0	8 plus reference oscillator

Table 1. Bandwidth, Modulation Index, and Channel Space as per Carlson

The reference oscillator for tape compensation will be the highest frequency in the composite signal at 960 kHz. If 12 kHz of guard spacing is available between bands, the overlap will only be of the seventh harmonic of the highest data frequency plus the carrier frequency. Table 2 provides actual harmonic amplitude relative to the carrier and indicates the position of that harmonic in the frequency band. To ensure a clear reference signal, the highest center frequency will be placed at 848 kHz. This ensures that any harmonic frequencies in the spectral region of and around the reference oscillator will have less than 0.01 percent amplitude referenced to the carrier amplitude.

For $f_{s\ max}$ = 10 kHz D = 3

Harmonic	Amplitude	Position
5	0.043	In band
6	0.013	In guard band
7	0.0025	In next band

Table 2. Harmonic Amplitudes and Positions

Tables 1 and 2 provide specifications on the number of channels per composite signal and harmonic content of each FM signal.

Unexpectedly large input amplitudes may drive the VCO hard enough to produce sidebands which occur in adjacent VCO ranges. For this reason the system requires that a positive and negative peak limiter process the signal first. Additionally, in the system described here, $f_{s\ max}$ must be kept at or below the values in table 2; otherwise, one VCO may produce sidebands in the frequency range allocated

to another VCO. Therefore, as good practice, an input filter must be included with each VCO. A three-pole Butterworth low-pass filter can be placed at the input of the VCO. This means that a 15 kHz input is attenuated by at least 11 db.

If the proposed system is to be economically competitive with other FM systems, the cost per channel must be held to a minimum. In this particular case, the limit was arbitrarily chosen to be $200.00 per channel, excluding transducers, cable, and recording equipment.

SECTION V

DETAILED SYSTEM DESCRIPTION

Figure 4 is the block diagram of the proposed forward multiplex system. The input is presumed to be a single-ended voltage, and the output feeds into a 1 MHz wide band channel to the recording vans. Each functional block requires ±15 volts power except the sine wave VCO and the reference oscillator which require +15 volts only.

Figure 5 is the detailed schematic of the peak clipper, the active filter, and sine wave VCO. U2 is a conventional self-compensated LM318 operational amplifier configured as an inverting amplifier with a gain variation of zero to -100. The nominal input impedance is 100K ohms or greater. Resistor R5 provides offset control over U2 and over any residual imbalance on the input signal. Resistor R10 adjusts the gain of U2. Diodes D5 and D6 are Zener diodes and limit the output (pin 6) of U2 at ±6.2 volts. A change in gain affects the offset adjustments. The gain adjustment should be made first and the offset second.

U1 is also an operational amplifier which, along with R11, R12, C9, and C10, forms a two-pole active filter. Resistor R13 and capacitor C11 complete a three-pole active filter with a Butterworth response. This low-pass filter has a zero frequency gain of 1.

U3 is the sine wave producing VCO chip (in this case an XR2206), the center frequency of which is determined by C12, R15, and R16. Resistor R14, in conjunction with the clipping diodes D5 and D6, determines the frequency swing. Resistors R18, R20, R21, and R22 are the bias level, amplitude, symmetry, and distortion controls of the sine wave output.

The MC1468R converts ±24 volts to ±15 volts regulated for the transducer. This supply can provide 100 mA of current at the regulated voltage.

Figure 6 is the detailed schematic of the reference oscillator, the FM mixer, the voltage regulator, and the calibration circuit. This circuitry is on one printed circuit card called the mixer card.

The crystal oscillator is a simple clapp oscillator with a field effect transistor and a 960 kHz crystal in the feedback circuit.

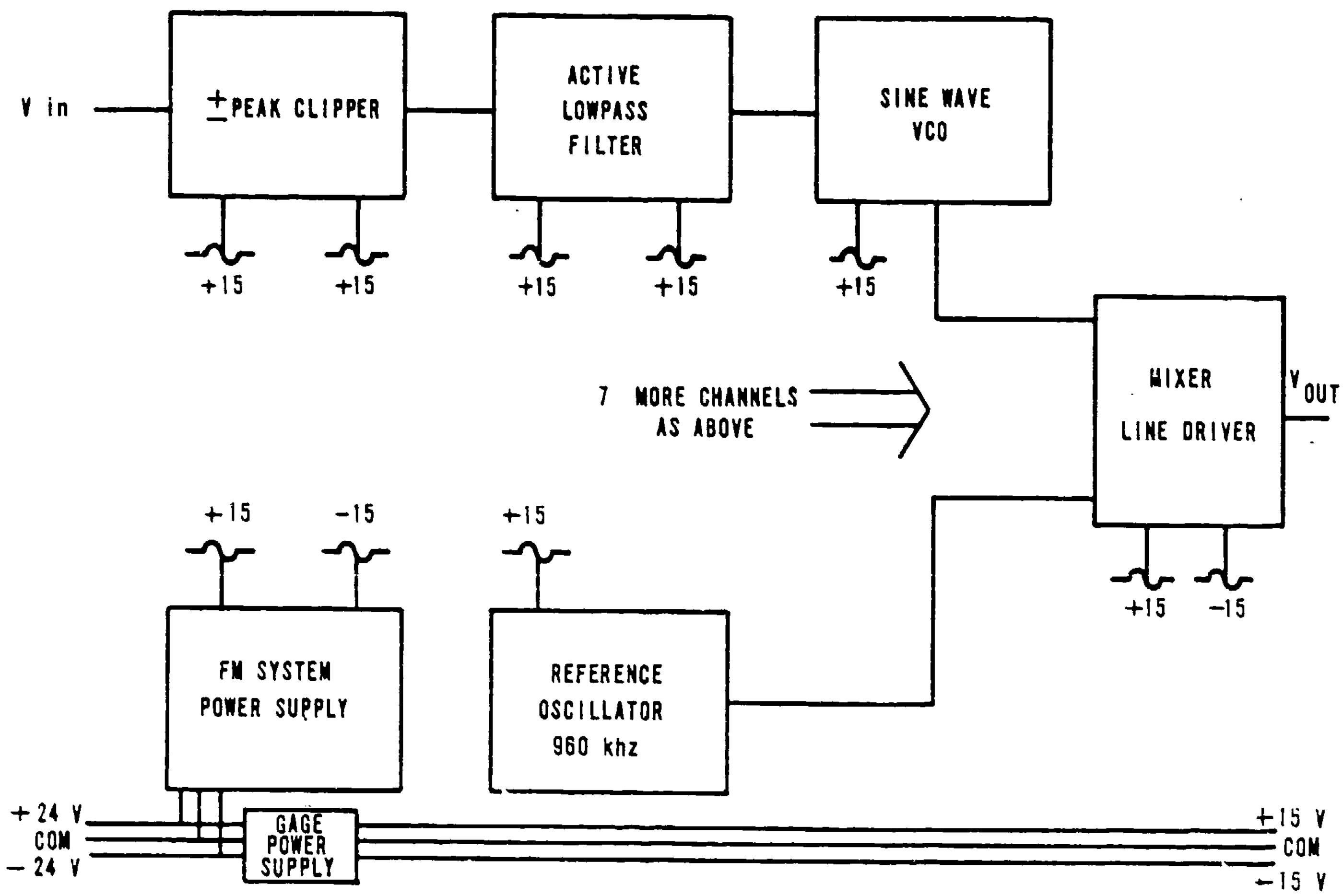
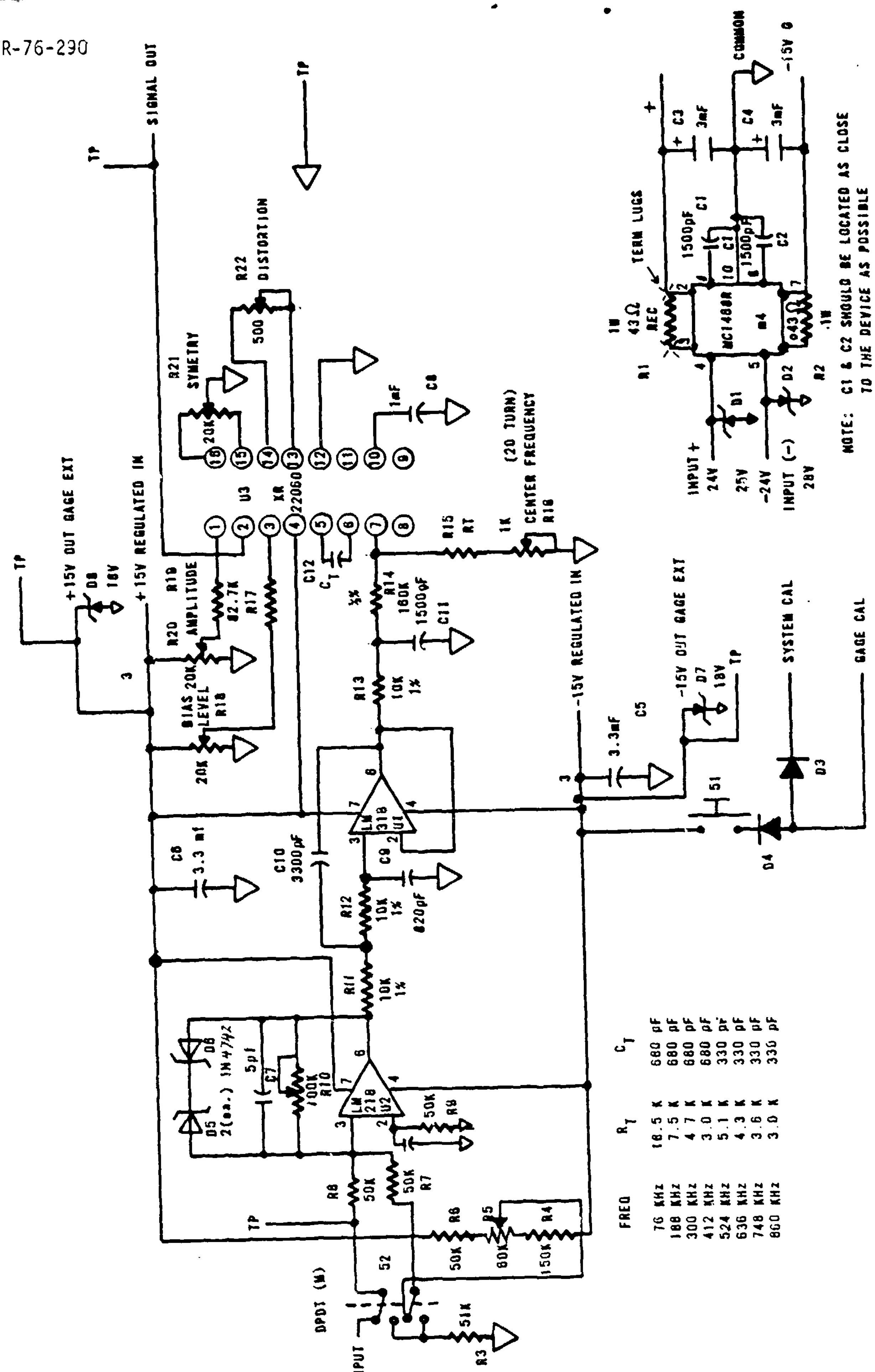


Figure 4. FM Multiplex System Block Diagram



FREQ	R_T	C_T
76 KHz	18.5 K	680 pF
188 KHz	7.5 K	680 pF
300 KHz	4.7 K	680 pF
412 KHz	3.0 K	680 pF
524 KHz	5.1 K	330 pF
636 KHz	4.3 K	330 pF
748 KHz	3.6 K	330 pF
860 KHz	3.0 K	330 pF

Figure 5. Clipper, Filter and VCO

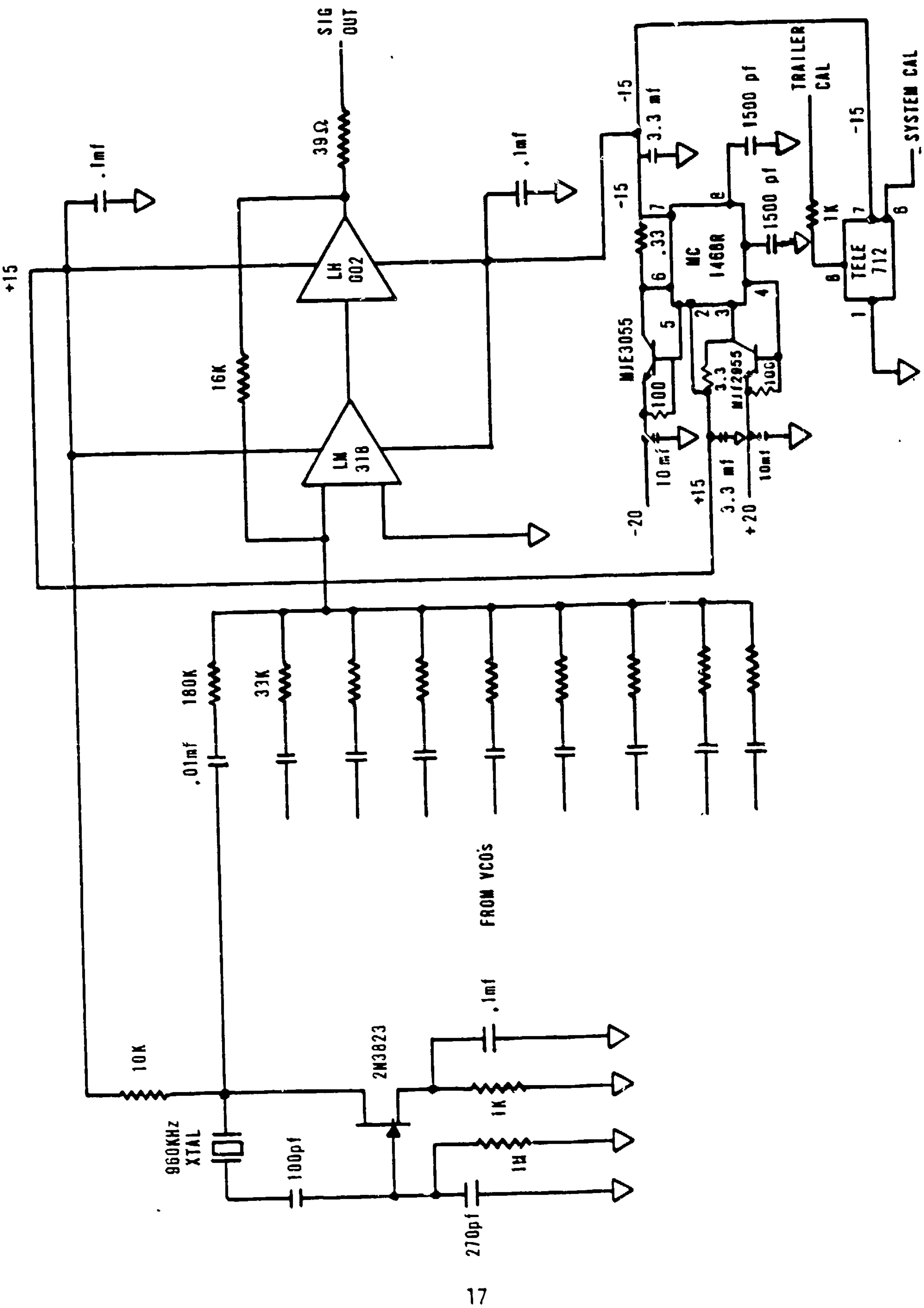


Figure 6. Crystal Oscillator, Mixer/Line Driver

The mixer is an LM318 and LH002 driver combined as a single feedback summing amplifier.

The voltage regulator for the mixer and VCO is on the mixer card. The gage calibration relay is also on this card. The regulator simply converts unregulated ±24 volts to regulated ±15 volts for the FM system (excluding the gage power whicn is provided by a regulator on each VCO card). The gage calibration relay provides the calibration signal by applying -15 volts to the gage calibration trigger line.

Table 3 provides the actual frequency assignments for the VCO's and the percent deviation. The deviation ratio of three is constant for all channels.

Channel No.	Center Frequency (kHz)	% Deviation
1	76	39.47
2	188	15.96
3	300	10.00
4	412	7.28
5	524	5.73
6	636	4.72
7	748	4.01
8	860	3.49
Ref Oscillator	960	-

Table 3. VCO Frequency Assignments

SECTION VI

TRANSMISSION, RECORDING, AND DEMODULATION

The system as described was designed to drive up to 5000 feet of RG58U coaxial cable when used with eight channels and a reference oscillator. Each channel may be set in amplitude to provide for pre-emphasis. By proper adjustment of each channel, the attenuation over various lengths of cable can be compensated. The tape recorder must be capable of handling frequencies up to the reference oscillator frequency of 960 kHz. Since the VCO center frequencies were determined for the maximum number of data channels rather than by IRIG standards, the normal IRIG discriminators cannot be used on this system. Presently, the Air Force Weapons Laboratory data reduction facility has tunable discriminators which work very well in demodulating the system described. These discriminators are of the phase lock loop type.

SECTION VII

LABORATORY TEST RESULTS

The prototype system was tested for linearity, temperature stability, and supply voltage sensitivity. Distortion tests were conducted in the AFWL/DE laboratories. The test results are presented in table 4.

Distortion (relative to fundamental)	
Second Harmonic	-40 db (spectrum analyzer)
Third Harmonic	-40 db
Fourth & Higher	-50 db or better
Intermodulation	-32 db
Linearity	0.1% best fit
Temperature Drift	-0.0125%/°C mica capacitor
Supply Voltage Sensitivity	Not measurable
Amplitude Modulation	Less than 5%

Table 4. Test Results

Discussion of Test Results

The measured linearity and power supply sensitivity are excellent. Limiting action is quite good. Using a mica capacitor for the frequency determining capacitor results in a negative temperature coefficient of frequency, whereas a polystyrene capacitor gives a positive temperature coefficient. Obviously, a mixed capacitor or different type of capacitor could yield a near zero temperature coefficient.

A minor amplitude modulation (AM) was observed in the highest frequency channel. This is not considered detrimental. The importance of AM is dependent on the type of discriminator used for modulation. A phase lock loop discriminator for example will not respond to low levels of AM.

The consequences of harmonic distortion and intermodulation distortion are difficult to predict with any degree of accuracy*; however, various bounds can be set on the amount of data distortion caused by interfering signals within a data channel. The amplitude of a distorting signal within a data channel is proportional to the difference between the channel carrier frequency and the interfering signal frequency; i.e., the beat signal frequency. When the interfering signal is at the edge of the demodulator output passband, the relative amplitude of the interference compared to the carrier amplitude within a channel is attenuated by a factor of twice the deviation ratio. For this case, the attenuation is at least a factor of six or 16 db. From the test results cited above, distortion products can be expected to cause less than 1% data distortion.

A seven-channel prototype system was further tested by providing a 5 kHz sine wave to all but the lowest channel. The composite signal was recorded on a VR3700B tape recorder, while the lowest channel (channel 2) was overdriven in amplitude, then frequency, and then both. The tape was then played back through tunable discriminators and each channel output observed on an oscilloscope. No distortion or crosstalk was observed on the higher channels (two through seven). The procedure was then repeated while overdriving each of the higher channels in turn. Again no distortion or crosstalk was observed on the other channels (those being properly driven).

*Note that most mathematical treatments of FM distortion include a factor relating to sideband attenuation caused by modulator output filters. This system has no output filter in the modulator; consequently, many of the standard "rules of thumb" do not apply. See "Aerospace Telemetry," Vol. II, pp. 83-93, by Stiltz, for examples.

SECTION VIII

CONCLUSIONS

The modulation system and hardware described here provide a great advantage in measuring phenomena associated with high explosive testing. By converting the transducer output to the noise-immune form provided by frequency modulation before the signal is sent over the hostile land line environment, a greater dynamic measurement range is achieved. By multiplexing eight channels of data on one coaxial line from the test bed to the recording van, a significant savings in cable may be realized.

Field testing of the system may now proceed. The remaining problems consist of properly interfacing the system to the various types of transducers and to the recording van. For proper operation, the recording van should have discriminators available to check proper operation of the system before the actual test event.

This system, which costs less than $200 per channel to build, is only possible because of the significant advances made in integrated circuit technology. In particular, the development of the sine wave producing voltage controlled oscillator has made low-cost high-performance frequency-modulated multiplex systems available for instrumentation purposes.

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